

MEASURING CAMERA ATTITUDE

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CLAIM OF PRIORITY

This Application claims the benefit of U.S. Provisional Application No. 60/166,725, Measuring Camera Attitude, filed on November 22, 1999. That Provisional Application is incorporated herein by reference.

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BACKGROUND OF THE INVENTION

Field of the Invention

The present invention is directed to a system for using camera attitude sensors.

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Description of the Related Art

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The remarkable, often astonishing, physical skills and feats of great athletes draw millions of people every day to follow sports. In particular, the number of people watching sports on television and the amount of advertising revenue received for televised sports has increased significantly. To satisfy the increased demand for televised sports, broadcasters have deployed a varied repertoire of technologies to highlight these exciting events for viewers. For example, broadcasters have started adding graphical enhancements to the video of the sporting events. Examples of graphic enhancements have included highlighting moving objects, highlighting portions of a playing field (e.g. first down line), adding virtual advertisements and the addition of other graphics to the video of the event.

The systems being employed for providing graphical enhancements to video have generally fallen into two categories. The first category of systems uses pattern

recognition to recognize certain features in the video in order to accurately place the graphic into the video. A second category of systems uses sensors to measure the attitude of the camera capturing the video and then uses the measured camera attitude information to accurately insert the graphic into the video. It has been
5 found that prior systems that only use pattern recognition have not been robust enough to account for rapid movement of the camera during the event and may be too slow for live events. Some systems that use pattern recognition have attempted to compensate for these deficiencies by using camera attitude sensors in combination with pattern recognition.

10 Systems that rely on camera attitude information require precise measurements of the orientation of a camera at any given time. Certain situations beyond the broadcaster's control can interfere with and be a source of error when measuring camera attitude information. For example, cameras at a sporting event typically are located at predesignated camera locations. Sometimes the camera
15 location has a floor that can sag or wobble. As a heavy camera is panned and tilted, the weight distribution of the camera and/or operator may cause the floor to sag or wobble. A camera operator moving at the camera location may also cause the floor to sag or wobble. Additionally, during an event, the tripod holding the camera can be kicked or moved. The floor of the camera location can also vibrate at either a
20 high frequency or low frequency because of other activity in the stadium, for example, fans jumping, fans stomping their feet, etc. Additionally, mechanical compliance of the various parts of the tripod and mount can also hinder an accurate camera attitude reading.

25 Thus, there is a need for an improved camera attitude measurement system to better measure camera attitude in light of the sources of error described above.

SUMMARY OF THE INVENTION

5 The present invention is directed to an improved system for using attitude sensors with a camera. The camera can be part of a camera assembly which includes a movable portion and a fixed portion. One example of a camera assembly includes a tripod base, a tripod head interface mounted on the tripod base, a tripod head mounted on the tripod head interface and a camera mounted on the tripod head. In one embodiment, the system includes a first sensor coupled to the camera assembly and a first inclinometer coupled to the camera assembly. Instead of, or in addition to, the first inclinometer, the system could have a first gyroscope ("gyro") coupled to the camera assembly. The first sensor measures the position of the moveable portion of the camera assembly relative to the fixed portion of the camera assembly. In one embodiment, the first sensor is an optical encoder. In one alternative, the system includes two optical encoders, two inclinometers and three gyros. Data from the camera attitude sensors are combined to describe the orientation of the camera. One means for describing the orientation of the camera includes setting up one or more transformation matrices. Alternatively, the data from the various camera attitude sensors can be combined to result in a set of angles describing the orientation of the camera. This information can be displayed on a monitor, printed, stored on a computer readable storage medium or passed to a software process.

15 The output of the camera attitude sensors are typically communicated to a camera sensor electronics package which receives the camera attitude data and packages the data for communication to graphics production equipment. In one embodiment, the data from the sensors is encoded on an audio signal and sent to the graphics production equipment (usually located remotely from the camera) via an audio line (or microphone line) from the camera. In one use of the present

invention, the graphics production equipment receives the sensor data, demodulates the audio and uses the camera attitude data to add a graphic to a video image from the camera. In one alternative, the graphic corresponds to a three dimensional location within a field of view of the camera. The three dimensional location corresponds to a first position in the video image, and the graphic is added to the video image at the first position. In one embodiment, the three dimensional location is converted to the first position in the video image using one or more transformation matrices.

One method for practicing the present invention includes sensing data from a first sensor, sensing data from a second sensor and combining the data from the two sensors. In one embodiment, the second sensor can be a gyro or an inclinometer. The first sensor measures relative position of the movable portion of the camera assembly with respect to the fixed portion of the camera assembly

Portions of the above-described process are performed using the sensors described above in combination with various hardware and software. The software for implementing the present invention can be stored on processor readable storage media. Examples of suitable processor storage media include RAM, ROM, hard disk, floppy disk, CD-ROM, flash memory, etc. In another alternative, the method can be performed on specialized hardware designed to specifically perform the functionality described herein.

The hardware and software described to perform the present invention can be used for purposes of adding one or more graphics to live or delayed video of a sporting event. Alternatively, the hardware and/or software of the present invention can be used to determine attitude information for other purposes, for example, enhancing video of non-sporting events and for determining attitude for purposes other than enhancement of video.

These and other objects and advantages of the present invention will appear more clearly from the following description in which the preferred embodiment of the invention has been set forth in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A shows a camera mounted on a tripod.

Figure 1B shows an exploded view of the tripod head interface.

Figure 1C is an exploded view of a portion of the tripod head interface.

Figure 1D is a bottom view of a portion of the tripod head interface, showing the camera lens panned at three different angles.

Figure 2 is a block diagram of the electronics associated with the camera attitude sensors.

Figure 3 is a block diagram of the interface electronics for an inclinometer of the present invention.

Figure 4 is a block diagram of the audio modulation circuit used in one embodiment of the present invention.

Figure 5 is a block diagram of the graphics production hardware.

Figure 6 is a block diagram of the audio demodulator circuit of Figure 5.

Figure 7 is a flow chart of one embodiment of a method of determining camera attitude information using an inclinometer with an encoder.

Figure 8 depicts one embodiment of a method of determining camera attitude information using a gyro and an inclinometer.

Figure 9 depicts one embodiment of compensating for gyro offset.

Figure 10 depicts one embodiment of determining camera attitude information using a gyro and an encoder.

Figure 11 is a flow chart describing one method of using camera attitude

information to enhance video.

DETAILED DESCRIPTION

5 Figure 1A shows a camera mounted on a tripod, using the sensors of the present invention. Specifically, Figure 1A shows camera 2 with lens 4 and viewing monitor 6. Camera 2 is mounted on tripod head 8. Tripod head 8 (also called a pan-tilt head) is mounted on tripod head interface 10, which is mounted on tripod 12. Tripod head 8 allows camera 2, lens 4 and monitor 6 (collectively referred to as "camera") to pan and tilt. One example of a suitable tripod head is the Vector 10 70 from Vinten, Inc. Although it is called a "tripod head," tripod head 8 need not be used with a tripod. The term tripod head is used to describe an apparatus that allows a camera to change its orientation (e.g. pan and tilt). Tripod head interface 10 is mounted between tripod head 8 and tripod 12, and includes some of the sensors and electronics of the present invention. For example, shown in Figure 1A 15 inside tripod head interface 10 are pan encoder 18, inclinometer 28 and inclinometer 30. Mounted to the outside of tripod head interface 10 is box 14, which houses camera sensor electronics 16.

Tilt encoder 20 has a shaft. That shaft is coupled to top platform 86 of tripod head 8 (see Figure 1B). Top platform 86 is mounted to camera 2. As 20 camera 2 and top platform 86 tilts, the shaft of encoder 20 will rotate. In one embodiment, encoders 18 and 20 shown in Figure 1 are optical shaft encoders. One example of an appropriate encoder is the CP-850 series encoder (including CP-850-HCE-131072) manufactured by Computer Optical Products, Inc., 9305 Eton Avenue, Chatsworth, California 91311. The CP-850 series encoder is an optical 25 shaft encoder. Other suitable encoders can also be used. The encoders measure rotational position relative to the tripod and/or tripod head interface. For example,

tilt encoder 20 measures movement of top platform 86 about a tilt axis in relation to tripod head interface 10. Pan encoder 18 measures the rotational position of platform 86 (as well as the camera and lens) about a pan axis in relation to tripod head interface 10. As will be discussed below, inclinometers 28 and 30 can be used to measure changes in the pan axis and the tilt axis.

One example of a suitable inclinometer uses liquid between a pair of plates, and measures change of capacitance. Another example is an electrolyte varying the conductance between two conductors. In one embodiment, a suitable inclinometer indicates an absolute angle (relative to gravity or other acceleration). In one example, the inclinometer can indicate angles up to plus or minus one degree, plus or minus 1.5, degrees, or plus or minus six degrees. Other suitable ranges can also be used. An example of a suitable inclinometer is the Ceramic Tilt Sensor SH50054 from Spectron, 595 Old Willets Path, Hauppaug, New York 11788, (516) 582-5600. Other suitable inclinometers can also be used with the present invention.

Looking back at Figure 1 A, mounted on top of lens 4 is block 22. Mounted on one surface of block 22 is gyro 24. Mounted on a second surface of block 22 is a second gyro 26. The surface that gyro 24 is mounted on is orthogonal to the surface that gyro 26 is mounted on. In one embodiment, an additional gyro is mounted on a surface orthogonal to gyro 24 and gyro 26. In another embodiment, the gyros (two or three gyros) can be mounted on tripod 12 or on tripod head interface 10. For example, the gyros can be mounted to plate 80 or another portion of tripod interface 10. When mounted on tripod interface 10, it is advantageous to mount two of the gyros in a fixed parallel relation to the inclinometers, that is, one gyro is aligned to read data for the same axis as one inclinometer. In another embodiment, references 28 and 30 can represent both an inclinometer and a gyro. Mounting the gyros on tripod interface 10 simplifies the math used for the present

invention. While the encoders measure angles relative to a fixed base, the gyros measure absolute angular rate with respect to an internal frame.

5 In one embodiment, the gyros of Figure 1 are fiber optic gyros. An example of a suitable fiber optic gyro is the E-Core 2000 Series Fiber Optic Gyro manufactured and sold by KVH Industries, Inc., 50 Enterprise Center, Middleton Road, Rhode Island 02842. Other gyros that can also be used include a ring laser, mechanical gyro, tuning fork, spinning disk gyro, semi conductor gyro, etc. Other sensors can also be used that measure change in angle or angular rate. The output of the E-Core 2000 Fiber Optic Gyro is an analog signal proportional to its angular rate. Integrating the output of the gyro over a period of time will produce an angle delta for that period of time. That is, the result of integration will indicate that the gyro was just rotated by a certain angle. The gyros used in Figure 1A are single axis. However, multi-directional gyros or multiple gyros can also be used. In one embodiment, the system can use three or more gyros instead of two, in order to measure pitch, roll and yaw. The gyros can be used to measure high frequency vibrations and mechanical compliance between portions of the camera assembly. In one alternative, rather than using an angular rate gyro, the system can use an absolute angle gyro.

20 Figure 1B shows an exploded view of tripod head interface 10. In one embodiment, the components of tripod head interface 10 are surrounded by a housing, which is not depicted in Figure 1B. The components of tripod head interface 10 are shown below tripod head 8 and above tripod 12. Plate 80 is coupled to tripod 12 using screw 32. Plate 80 is also mounted to mount 40 using screws 34, 36, 38 and screw 82 (screw 82 is shown in Figure 1C). Mount 40 is attached to block 50 using screws 44, 46 and 48. Mounted inside block 50 is pan encoder 18. Block 50 includes a triangular portion which protrudes out from the

bottom of block 50 (see Figure 1C) causing a separation between block 50 and mount 40. Residing in the space between block 50 and mount 40 is arm 56 which is connected to member 54 using screw 60. Located between member 54 and arm 56 is a self aligning spacer 58.

5 As will be shown in Figures 1C and 1D, arm 56 is coupled to the shaft of pan encoder 18. Member 54 is coupled to tripod head 8. As tripod head 8 rotates (pans), arm 56 also rotates, which causes the shaft of pan encoder 18 to rotate, thereby, allowing pan encoder 18 to measure the rotation or pan of the camera.

10 Mounted on one surface of block 50 is inclinometer 30. Mounted on a second surface of block 50 is a second inclinometer 28. The surface that inclinometer 28 is mounted on is orthogonal to the surface that inclinometer 30 is mounted on. Mounted in front of inclinometer 30 is a PC board 84. Inclinometer 28 and inclinometer 30 are both connected to PC board 84. In one embodiment, PC board 84 includes electronics that are in communication with camera sensor
15 electronics 16. Block 50 includes four holes 72, 74, 76 and 96 (hole 96 is shown in Figure 1C) that house screws for mounting block 50 to plate 100 (see Figure 1C).

As described above, one embodiment that simplifies the math includes mounting the gyros on plate 80. In one embodiment, plate 80 depicted in Figure 1B would be re-designed so that it was a unitary structure with two portions. The first
20 portion would be circular with mounting holes as depicted in Figure 1B. The second portion would include a beam protruding from the circular portion. In one alternative, the beam would extend six inches. Three gyros are mounted on the beam such that the three gyros are mounted orthogonal to each other.

Figures 1C shows additional details of tripod head interface 10. Specifically,
25 Figure 1C shows arm 56 engaging shaft 98 of encoder 18. At the end of arm 56 is end portion 90 coupled to arm 56 via screws 92 and 94. Member 54 is mounted on

plate 102 via two screws that are not shown in the drawings. Plate 102 is mounted to tripod head 8 so that when tripod head 8 rotates (pans) then member 54 and arm 56 are also rotated about the pan axis, causing shaft 98 to rotate and allowing encoder 18 to measure that rotation. The screws residing in holes 72, 74, 76 and 96 mount block 50 to plate 100. Plate 100 is coupled to plate 102 using bearings so that plate 102 will rotate with respect to plate 100. In the embodiment depicted in Figures 1A-1D, plate 80, mount 40, block 50 and plate 100 are stationary with respect to tripod 12. As tripod head 8 is rotated about the pan axis, the camera and plate 102 also rotate.

Figure 1C also shows more detail of the coupling of mount 40 to block 50. Specifically, triangular portion 88 and block 50 are shown in more detail. Because triangular portion 88 is raised from the remaining portion of the bottom surface of block 50, there is sufficient space between block 50 and mount 40 to allow for the presence of arm 56. Additionally, block 50 is contained within a housing.

Figure 1D shows lens 4 in three different positions (4, 4' and 4"). As can be seen, as lens 4 is moved to position 4', arm 56 is rotated to position 56'. As lens 4 is rotated to position 4", arm 56 is rotated to position 56". As arm 56 is rotated to position 56' and 56", shaft 98 is similarly rotated.

Figure 2 shows a block diagram of the electronics for using the camera attitude sensors. Figure 2 shows pan encoder 18, tilt encoder 20, gyro 24, gyro 26, inclinometer 28 and inclinometer 30. The output of pan encoder 18 and tilt encoder 20 are sent to FPGA 212. Pan encoder 18 and tilt encoder 20, in one embodiment, are optical encoders that output a signal, measured as a number of counts (or pulses), indicating the rotation of shaft. The output signal is a quadrature signal indicating rate and direction. FPGA 212 decodes the signal from the shaft encoders to output a count. FPGA 212 also controls analog to digital converter 214 and

provides interface logic for processor 216. In regard to the analog to digital converter 214, FPGA 212 provides interface logic and a buffer, including a register to store a value for each sensor connected to analog to digital converter 214.

5 Gyro 24 is connected to interface board 220, which is connected to analog to digital converter 214. Interface board 220 comprises electronics for receiving a signal from gyro 24 and presenting the information to analog to digital converter 214. The electronics of board 220 includes a differential amplifier and other electronics which can reject common mode noise and amplify the signal from the gyro. The output of gyro 26 is connected to interface board 222. Interface board 10 222 operates in the same manner as interface board 220 and is also connected to analog to digital converter 214.

Signal 224 represents the electrical output of the zoom lens potentiometer of the camera and is connected to analog to digital converter 214. Signal 226 represents the electrical output of the 2X extender of the camera and is connected 15 to analog to digital converter 214. Signal 228 represents the connection to the lens of the camera, provides the value of the focus of the camera and is connected to analog to digital converter 214.

The output of inclinometer 28 is connected to interface board 230. The output of inclinometer 30 is connected to interface board 232. The outputs of 20 interface board 230 and interface board 232 are both connected to analog to digital converter 214. Analog to digital converter 214 converts the input analog signals to digital signals, and sends the output digital signals to FPGA 212. FPGA 212 includes a register for each of the sensors. In one embodiment, the electronics of interface boards 230 and 232 are included on PC board 84. In one alternative, PC 25 board 84 can include electronics and LEDs to indicate when tripod head 8 is level.

Processor 216 is in communication with data memory 236 for storing data

and program memory 238 for storing program code. In one alternative, memory 238 is a flash memory and memory 236 is a static RAM. In one embodiment, processor 216 is an 8032 processor from Intel. Processor 216 also receives an output signal from sync decoder 240. Sync decoder 240 receives a video signal 250
5 from camera 2. Sync decoder 240 generates a sync signal so that the data from the sensors can be synchronized to the video. In one embodiment, the video is transmitted at 30 frames per second. Other video rates can also be used. Processor 216 assembles data from each of the sensors into a packet and sends the data to modulator 244. Processor 216 assembles the data using the sync signal so that data
10 is collected and sent in synchronization with the video from the camera. For example, data can be sent for every field, every video frame, every other video frame, every third video frame, etc. In one embodiment, the packet of data sent from processor 216 does not include time code or any type of synchronization signal.

15 Modulator 244 receives the packet of data from processor 216 and encodes data for transmission on an audio frequency signal. The output of modulator 244 is sent to audio driver 246 and coax driver 248. Most broadcast cameras have a microphone input channel. The output of audio driver 246 is sent to the microphone input channel for camera 2. The camera then combines the audio input
20 channel with the video and sends a combined signal to the production equipment. If the audio signal is needed on a coax cable, then that signal is received from coax driver 248. In one embodiment, there can also be an RS232 or RS422 output directly from processor 216.

25 Figure 3 is a block diagram of interface boards 230 and 232. Note, in one embodiment, interface board 230 and 232 can be combined as one board with two inputs and two outputs. Figure 3 shows sensor 300, which can be inclinometer 28

or inclinometer 30. One input to sensor 300 is oscillator 302, which provides a 2.5 KHz square wave. Sensor 300 has two outputs. One output is connected to one end of resistor 304 and the positive terminal of differential amplifier 308. The other output is connected to one end of resistor 306 and the negative terminal of differential amplifier 308. The other ends of resistor 304 and 306 are connected together and to ground. The output of differential amplifier 308 is sent to multiplier 310. The output of oscillator 302 is also sent to multiplier 310. In one embodiment, multiplier 310 operates to convert the output of amplifier 308 to a DC signal. The output of multiplier 310 is sent to low pass filter 312 which removes noise, specifically the 2.5 KHz oscillator signal. In one embodiment, low pass filter 312 has a 40 Hz cut off frequency. The output of low pass filter 312 is sent to amplifier 314. The output of amplifier 314 is a linear voltage output indicating inclination angle. In one embodiment, the dynamic range of the circuit of Figure 3 is plus or minus 1.5 degrees.

Figure 4 is a block diagram of modulator 244 of Figure 2. The input of modulator 244 is first sent to FEC and Interleave unit 340, which receives the data, adds forward error correction and error detection information (cyclic redundancy check - CRC) and interleaves the result for burst-error protection. The output of FEC and Interleave unit 340 is sent to data pump 342, which converts the data into a four level analog signal. The output of data pump 342 is sent to low pass filter 344. The output of data pump 342 is said to be in the form of level coded symbols. The output of low pass filter 344 is sent to a voltage controlled oscillator 348 which is used to modulate an audio signal with a 10 KHz center frequency (also called FM for "frequency modulation"). The output of voltage controlled oscillator 348 is sent to amplifier 350. The output of amplifier 350 is sent to transformer 352. The output of transformer 352 is sent to the microphone input channel of a video camera

via audio driver 246. Figure 4 shows box 346 drawn around FEC and Interleave unit 340, data pump 342 and low pass filter 344. In one embodiment, the functions inside box 346 are performed by a MX919 4-Level FSK Modem Data Pump from MX•COM, Inc., 4800 Bethania Station Road, Winston-Salem, North Carolina
5 27105, (800) 638-5577, www.mxcom.com.

Figure 5 is a block diagram of the graphics production equipment. In one embodiment, the equipment depicted in Figure 5 is used in a truck at an event. Alternatively, the equipment can be in a studio or another suitable location. Audio demodulator 400 receives audio signal(s) from one or more cameras. In one
10 embodiment, it receives audio signals from three cameras. In alternative embodiments, audio demodulator 400 can receive audio signals from less than three cameras (even one camera) or more than three cameras. Each of the audio signals includes data from the sensors associated with the camera providing the audio signal. Audio demodulator 400 extracts the data from the audio signal and sends
15 the data for each of the associated cameras to concentrator 402. Concentrator 402 receives the camera attitude data for sensors from one or more cameras and packages the data for transmission to computer 406. In one embodiment, concentrator 402 is a computer. Concentrator 402 also receives a time code from time code generator 404. The time code is packaged with the data from the various
20 sensors so that the data can be synchronized with the appropriate frame or field of video. In one embodiment, time code 404 is a VITC (Vertical Interval time Code) inserter. Time code generator 404 receives the tallied video signal and provides a time code, based on the received video, to concentrator 402. After time code generator 404, the video signal is sent to computer 406 and delay 410. In one
25 embodiment, a time code and a unique camera identifier are added to the vertical blanking interval of the video from the instrumented cameras. In another

embodiment, a time code is added to the sensor data at the camera location, prior to transmission to audio demodulator 400. Concentrator 402 also receives key data from another processor. The key data is used to indicate which colors in the video can be enhanced or blended with the new graphic. This allows the system to account for occlusions. More information about using key data can be found in U.S. Patent Application Serial No. 09/160,534, System For Enhancing a Video Presentation of a Live Event, Gloudemans, et al. and U.S. Patent Application Serial No. 09/425,992, filed on October 21, 1999, Attorney Docket No. SPTV-01038US0 BBM), Telestrator System, Meier, et al. both of which are incorporated herein by reference.

The combined data from the sensors is sent to computer 406. Computer 406, computer 408, delay 410 and keyer 412 are used to enhance live video from a chosen camera. The present invention works with various systems for enhancing the video. For example, suitable systems are described in the following patents/applications: U.S. Patent No. 5,912,700, A System for Enhancing the Television Presentation of an Object at a Sporting Event, U.S. Patent No. 5,917,553, Method And Apparatus For Enhancing The Broadcast of a Live Event, U.S. Patent Application Serial No. 09/041,238, System For Determining The Position Of An Object, filed January 6, 1998, U.S. Patent Application Serial No. 09/160,534, A System For Enhancing a Video Presentation of a Live Event, filed September 24, 1998, all of which are incorporated herein by reference.

Computer 406 receives the sensor data, key data and time codes from concentrator 402. Computer 406 also receives the video signal, including VITC. In one embodiment, computer 406 is used to choose a location on the playing field of a sporting event. The location can be chosen using any suitable means including a pointing device, a keyboard, or a software process. The three dimensional

coordinates associated with the chosen position are determined using any number of means in the art including using a model, prestoring locations, manually entering the locations, sensors (infra-red, radar, . . .) etc. Using the data from the camera attitude sensors, computer 406 converts the three dimensional location(s) of the

5 chosen location to two dimensional position(s) in the frame or field of video from the chosen camera. That two dimensional position(s) are sent to computer 408 to draw (or set up) a field or frame of video with the graphic. Computer 408 then sends instructions to a keyer to combine the graphic with the video from the camera. The video from the chosen camera is sent first to delay 410 in order to

10 delay the video a number of frames to allow for the processing of the camera attitude information and the other methods of computers 406 and 408. After being delayed, the video is sent from delay 410 to keyer 412 for combining with the graphic(s) generated by computer 408. The output of keyer 412 can be sent for broadcast or recorded for future use. In the embodiment described above, the

15 components operate in real time and enhance live video. In another embodiment, the camera attitude information can be used to enhance pre-stored video. An example of a graphic can be a line added to a video of a football game; a virtual advertisement; a cloud to show the location of a moving object; or any other suitable graphic.

20 In one embodiment, a third computer can be added to computers 406 and 408. The third computer can be used to provide a user interface which, among other things, allows an operator to choose which colors can be replaced with a graphic. This third computer would supply the key data to concentrator 402. In

25 this embodiment, computer 406 determines where within a given field or frame a graphic should be inserted and computer 408 draws the graphic and synchronizes the graphic with the appropriate field or frame.

Figure 6 is a block diagram of audio demodulator 400. Data is first sent to phase-locked-loop circuit 480. The output of phase-lock-loop circuit 480 is sent to filters 482. The output of filters 482 is communicated to low pass filter 484. The output of low pass filter 484 is sent to signal decoder 486, which reverts the four level analog signal back to a digital signal. The output of signal decoder 486 is sent to FEC Interleave module 488 which completes the forward error correction and accounts for the interleaving. The output of FEC and Interleave module 488 is sent to concentrator 402. Box 490 is drawn around low pass filter 484, signal decoder 486 and FEC and Interleave module 488 to indicate that all three functions can be combined into one chip. For example, all three functions can be performed by using the MX919 chip from MX•COM, described above. The circuit of Figure 6 is used to operate on data for one camera. If data from multiple cameras is considered, then audio demodulator 400 will include multiple circuits like that of Figure 6.

Figure 7 is a flow chart describing one method for using the inclinometers with an optical encoder. In step 560, voltages are read from each of the inclinometer sensors (e.g. 28 and 30). In one embodiment, step 560 includes a signal being processed by interface boards 230 and 232 to analog to digital converter 214, and through FPGA 212 to processor 216. Processor 216 will read the appropriate values at the appropriate time according to the sync signal sent from sync decoder 240. In step 562, the data is passed through a low pass filter. In one embodiment, the low pass filter can be performed using hardware. In other embodiments, computer 406 can implement a low pass filter using software. The low pass filter could include averaging data over a period of time. For example, samples from 30 frames of data can be averaged. In one alternative, the data can be averaged by looking at 15 samples ahead in time and 15 samples behind in time.

The reason why there are samples ahead in time is because the video is delayed by frame delay 410. Other time frames other than samples of 30 frames or 30 fields can also be used.

5 In step 564, the values read from the inclinometers are converted to a camera attitude parameter for use by the production equipment. For example, the voltages can be converted to angles. One means for converting voltage to an angle is to use a look up table. In another embodiment, a scaling factor can be applied to the voltage to convert the voltage to an angle. The angle can be expressed in degrees, radians or another unit of measure. Rather than converting the voltage to
10 an angle, the voltage can be converted to a different form of an attitude parameter (e.g. such as a variable in a matrix).

In step 568, the system reads the encoder. Note that step 568 may be performed at the same time as step 560. Step 568 includes FPGA 212 receiving data from one of the encoders and providing that data to processor 216. Processor
15 216 will read the data in accordance with the sync signal from sync decoder 240. In step 570, the data from the encoder is converted to a camera attitude parameter for use by the production equipment. For example, the voltage can be converted to an angle. In step 572, the parameter from the encoder is combined with the parameter(s) from the inclinometer(s). Remember that the encoder measures the
20 amount of rotation of the camera with respect to the base. In one embodiment, the inclinometers measure attitude of the base. Thus, the actual orientation is determined by using information from both encoders and both inclinometers. The inclinometers can be thought of as measuring roll and pitch of the tripod, while the pan encoder measures pan angle of the camera with respect to the base of the tripod
25 or in relation to the tripod head interface. The pan axis is moved from a completely vertical axis to a different orientation based on roll and/or pitch. A similar analysis

applies for tilt. One method for performing step 572 is to create one or more transformation matrices (to be used in step 712 of Fig. 11). Another embodiment uses different means known in the art for summing angles from different sensors.

Figure 8 explains one method for combining a gyro with an inclinometer.

5 The embodiment of Figure 8 assumes that the gyros are mounted on the tripod head interface 10 such that for each inclinometer there is a gyro mounted to measure data for the same axis. One gyro and one inclinometer are mounted on the pitch axis. Another gyro and inclinometer are mounted perpendicular to the pitch axis devices in order to measure the roll axis. Each gyro and inclinometer pair are independently used to measure pitch and roll. An additional gyro or gyro/inclinometer pair can also be used to measure yaw. The system of Figure 8 is used to measure pitch. An identical system is used to measure roll.

10 Gyro 610 is a fiber optic gyro which measures angular rate. It does not have any reference to absolute angle. It can accurately measure the relative angular change. The output of gyro 610 is integrated using a digital or analog integrator 614. The output of integrator 614 will represent an angle. The output of integrator 614 is scaled (block 624). We can describe the measured output of the integrated gyro signal as $A_G = A + e_G$ where A_G = integrated angle, A = actual angle gyro 610 was rotated and e_G = error induced by gyro 610. The error e_G is largely due to the offset drift of the gyro and only has low frequency components.

15 Inclinometer 604 can accurately measure the true pitch or roll of the camera mount but is subject to acceleration errors. Gravity and acceleration of a reference frame are indistinguishable, so it is difficult to tell the difference between gravity indicating which way is "down" and acceleration imposed on the sensor. Imagine that the camera mount is not disturbed and is on a very stable platform. The inclinometer will accurately read the angle of the camera mount because the only

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force acting on the inclinometer is gravity. If the camera mount is tilted, it will accurately measure the new pitch or roll. During the transient when rotating the camera mount, acceleration will be induced on the sensor unless the axis of rotation is precisely through the inclinometer sensor and the pan axis is nearly frictionless.

5 The axis of rotation will typically not be through the inclinometer, so changes in pitch or roll will induce a transient error in the inclinometer reading. In addition to this error, the device being used has a slow response to transients. If the device is rotated rapidly about the axis so as not to induce acceleration errors, the response time is about one second. If we think about the inclinometer signal output errors
10 in the frequency domain, we can say that the low frequency errors are very small because the average acceleration will be near zero as long as we are not translating the inclinometer to a new position. Most of the inclinometer errors will be high frequency due to transient accelerations. Let $A_I = A + e_I$ where A_I = measured angle from inclinometer, A = actual angle inclinometer 604 was rotated and e_I = the
15 inclinometer measurement error due to acceleration and sensor response. The error e_I will have very little low frequency components.

Summer 616 will subtract A_G (output of scale block 624) from A_I (output of inclinometer 604) yielding $e_I - e_G$. This signal is passed through low pass filter (LPF) 618. The cutoff frequency of LPF 618 is chosen to pass the gyro error signal
20 e_g but reject inclinometer error signal e_I . A typical cutoff frequency is 0.2Hz. The output of LPF 618 will be $-e_G$. Summer 620 will add signal A_G from scale block 624 to $-e_G$ from LPF 618. The result is signal A , the desired actual angular rotation.

An enhancement to the method is to adaptively set the cutoff frequency of LPF 618. If the system is not experiencing any acceleration, it is advantageous to
25 raise the cutoff frequency to reduce errors due to drift in the gyro. If the system is experiencing accelerations, it is advantageous to lower the cutoff frequency to

reduce the errors due to the inclinometer. Acceleration errors will be seen as a high frequency signal at the output of summer 616. The output of summer 616 is sent to high pass filter (HPF) 626. The output of HPF 626 is then sent to a fast attack, slow decay detector 628. The output of detector 628 is used to set the cutoff frequency of LPF 618.

Figure 9 shows one embodiment for automatically compensating for gyro offset correction. If the gyro is not rotating, it will have some non-zero signal. If this non-zero signal is integrated, the resulting signal will be a ramp signal. In the embodiment where the gyro is mounted to a fixed portion of the camera assembly, over the long term the gyro is not rotating through a net angle. The average angle change is zero. Figure 9 shows the output of gyro 610 being sent to subtractor 630. The output of subtractor 630 is sent to integrator 614 and amplifier 632. The output of amplifier 632 is sent to integrator 636 and the output of integrator 636 is subtracted from the output of gyro 610 by subtractor 630. Subtractor 630, amplifier 632 and integrator 636 comprise a feedback system that generates an offset signal that cancels the gyro offset. After a period of time determined by the gain of amplifier 632, the signal at the output of integrator 636 will be equal to the offset of gyro 610.

In another enhancement, a gyro may be placed on the stationary portion of the camera assembly (e.g. tripod, tripod head interface) so it is sensitive to the pan axis. If the camera is panned very quickly, the camera mount may twist. The pan encoder 618 will not measure the amount of twist. A gyro will measure this twist and a correction can be applied to the resulting pan axis.

Figure 10 shows how the gyro may be high pass filtered and combined with the pan axis encoder. The output of gyro 610 is sent to integrator 640. The output of integrator 640 is sent to high pass filter 642. The output of high pass filter 642

is added (summer 644) to the output of pan encoder 618.

Figure 11 is a flow chart which describes how the camera attitude information is used by the system for enhancing video. In step 700, the system or an operator determines the location to be enhanced. That could be a location on a playing field, in a stadium or another location. For example, if the system is to enhance a broadcast of a football game by depicting a first down line (e.g. the line a player must cross to achieve a first down) or to add an offside line to a soccer telecast, the system or person can indicate the location on the field where the line should be drawn using any conventional input device (e.g. keyboard, pointing device, etc.). That location can be associated with one or more three dimensional coordinates. In one embodiment, the location is the current location of a moving object. In step 702, attitude data is read from the various attitude sensors (e.g. inclinometer, gyro, encoder, etc.). In many broadcasts of sporting events, multiple cameras are used. Thus, attitude sensors may be used with one or more cameras. Step 702 includes reading the attitude data for all the cameras. In some embodiments, step 702 can include reading data for only a subset of the cameras. In step 704, the attitude data for the cameras is added to the respective audio signal for the corresponding camera. In step 706, the system determines the tally. The tally indicates which camera is being used for broadcast. That is, there may be twelve cameras at a sporting event; however, usually only one camera is chosen for broadcast at any one given time. The system can determine the tally by having an automatic tally detector, looking for a unique camera identifier in the vertical blanking interval or reading tally information from other production equipment. One could even enter the tally manually by watching or listening to the director, etc. By knowing which camera is tallied, the system can determine which set of camera attitude data to use. That is, only the camera attitude data associated with the

camera tallied is used to enhance the video.

In step 708, the attitude information is extracted from the audio signals. In one embodiment, attitude information for all of the cameras are extracted from all the respective audio signals by audio demodulator(s) 400 and sent to concentrator 402 which then sends the combined signal to computer 406. In another embodiment, only the data from the tallied camera is extracted. In step 710, the system determines the attitude of the tallied camera. Determining the attitude can include the teachings of Figures 7-10. In one embodiment, the data from each of the sensors can be converted to appropriate parameters for insertion into transformation matrices. In step 712, the location(s) determined in step 700 are transformed to a two dimensional position in the frame or field of video from the tallied camera. Step 712 includes multiplying the determined location(s) by one or more transformation matrices, where the parameters of the transformation matrices are determined from the camera attitude data. In step 714, the video is enhanced by placing a graphic at the two dimensional location(s) determined in step 712.

The following discussion provides more detail in regard to steps 710 and 712 for an exemplar system using inclinometers, and/or gyros, with encoders. To convert a three-dimensional location to a two dimensional position, a four-by-four transformation matrix $[M_{w,c}]$ maps a four dimensional row vector representing the three dimensional location in world coordinates into a two dimensional position in camera coordinates.

There are four coordinate systems to consider: world coordinates, three dimensional camera coordinates, two dimensional camera (screen) coordinates and roll/pitch coordinates. The roll/pitch coordinates define the coordinate system with the inclinometers at or near the origin. The pan axis may or may not be vertical. The tilt axis may or may not be horizontal. Roll and pitch will describe the direction

vector of the pan axis and the tilt axis.

The world coordinates are the coordinates of the playing field or event. In the system for enhancing a football game, the world coordinates can be a system with the origin in the corner of the football field. The positive x-axis in world coordinates is defined by the sideline closest to the cameras, the positive y-axis in world coordinates is defined by the goal line to the left of the direction of the cameras and the positive z-axis points upward, perpendicular to the x-axis and y-axis. If the positive y-axis in world coordinates is rotated counter-clockwise Φ degrees around the positive z-axis so that the new positive y-axis is pointing in the same direction as the camera when the tilt of the camera is level (perpendicular to the direction of gravity) and the camera's pan encoder measures zero, then the pan offset for that particular camera is Φ . For the analysis below, assume that the roll is represented by the variable ρ and the pitch is represented by the variable ψ . The values ρ & ψ are the output A of summer 620 of Fig. 8. Roll and pitch are measured by the inclinometers alone, gyros alone, or a combination of inclinometers and gyros. Assume that because the roll and pitch changes the orientation of the pan axis (and perhaps the tilt axis), the new unit direction vector of the pan axis is given by the vector (v_1, v_2, v_3) . Then, the following equations define variables used in the matrices.

$$(v_1, v_2, v_3) \cdot (1, 0, 0) = v_1 = \cos(90^\circ - \rho) = \sin(\rho)$$

$$(v_1, v_2, v_3) \cdot (0, 1, 0) = v_2 = -\cos(90^\circ - \psi) = -\sin(\psi)$$

$$v_1^2 + v_2^2 + v_3^2 = 1$$

$$v_3 = \left(1 - v_1^2 - v_2^2\right)^{\frac{1}{2}}$$

$$(0, 0, 1) \cdot (v_1, v_2, v_3) = v_3$$

$$T = \arccos(v_3)$$

5 Additionally, assume that the origin of the roll/pitch axis (location of a fixed
point near inclinometers and/or gyros) in world coordinates is (rpx, rpy, rpz). Using
these variables, the matrix $[M_{w,c}]$ is created by multiplying a first matrix $[M_{w,rp}]$ by
a second matrix $[M_{rp,c}]$. The matrix $[M_{w,rp}]$ represents a transformation from world
10 coordinates to roll/pitch coordinates. The matrix $[M_{rp,c}]$ represents a transformation
from roll/pitch coordinates to two dimensional camera coordinates. The matrices
are defined as follows:

$$[M_{w,c}] = [M_{w,rp}] \times [M_{rp,c}]$$

The matrix $[M_{w,rp}]$ is defined by

15

$$[M_{w,rp}] = [T_{-rp}] [R_{z,-\Phi}] [R^T]$$

where

$$[T_{-rp}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -rpx & -rpy & -rpz & 1 \end{bmatrix}$$

20

$$[R_{z,-\Phi}] = \begin{bmatrix} \cos(\Phi) & -\sin(\Phi) & 0 & 0 \\ \sin(\Phi) & \cos(\Phi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$[R^T] = \begin{bmatrix} \frac{-v_1^2 + \cos(T) + 1}{(1 + \cos(T))} & \frac{-v_1 v_2}{(1 + \cos(T))} & v_1 & 0 \\ \frac{-v_1 v_2}{(1 + \cos(T))} & \frac{-v_2^2 + \cos(T) + 1}{(1 + \cos(T))} & v_2 & 0 \\ -v_1 & -v_2 & \cos(T) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix $[M_{rp,c}]$ is defined by

$$[M_{rp,c}] = [R_{z,\Phi}] [T_{rp}] [K]$$

5

where

$$[T_{rp}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ rpx & rpy & rpz & 1 \end{bmatrix}$$

$$[R_{z,\Phi}] = \begin{bmatrix} \cos(\Phi) & \sin(\Phi) & 0 & 0 \\ -\sin(\Phi) & \cos(\Phi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

5 The matrix $[R_{z,\Phi}]$ is the four-by-four matrix corresponding to a counter-clockwise rotation by Φ degrees around the positive z-axis. The matrix $[T_p]$ denotes a four by four matrix corresponding to a translation by (rpx, rpy, rpz). The
10 matrix $[R^t]$ is the inverse of the matrix which provides a transformation from roll/pitch coordinates to world coordinates. The matrix $[K]$ represents a transformation matrix for transforming a three dimensional location in world coordinates to a two dimensional position in camera coordinates for a system that uses encoders but does not use inclinometers or gyros, and is similar to the
15 transformation matrices described in U.S. Patent Application No. 09/160,534 and U.S. Patent No. 5,912,700, both of which are incorporated by reference. The matrix $[K]$ is defined as:

$$[K] = [T][A][D][B][C][G]$$

15

where the matrix $[G]$ is defined as

$$[G] = \begin{bmatrix} fh & 0 & 0 & 0 \\ 0 & fv & 0 & 0 \\ 0 & 0 & -(f+n)/(f-n) & -1 \\ 0 & 0 & -2fn/(f-n) & 0 \end{bmatrix}$$

The matrix [G] models the effective focal length of the lens as a function of zoom, focus, and 2X Extender settings. The variables n and f are the distances to the mathematical near and far clipping planes, which are only important in assigning a useful range for z-buffered graphics drawings; therefore, nominal values are used of n=1 yard and f = 100 yards. The variable fh is the effective horizontal focal length of the lens. The variable fv is the effective vertical focal length of the lens. The aspect ratio, which is constant, is fv/fh. A software routine is used to convert the appropriate zoom factor and aspect ratio to fh and fv.

The matrix [A] is defined as:

$$[A] = \begin{bmatrix} \cos(pan) & -\sin(pan) & 0 & 0 \\ \sin(pan) & \cos(pan) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix [B] is defined as:

$$[B] = \begin{bmatrix} \cos(twist) & 0 & \sin(twist) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(twist) & 0 & \cos(twist) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix [C] is defined as:

$$[C] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix [D] is defined as:

$$[D] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\text{tilt}) & -\sin(\text{tilt}) & 0 \\ 0 & \sin(\text{tilt}) & \cos(\text{tilt}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The matrix [T] is defined as

$$[T] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -lx & -ly & -lz & 1 \end{bmatrix}$$

The parameters in the above described matrices are discussed below.

- 10 The pan parameter is defined as (pan = pan/reg - ptzfdit.pan), where ptzfdit.pan is measured with the pan optical encoder during the event. The variable pan/reg is determined using the pan optical encoder prior to the event. First, the camera's optical center is pointed to a known fiducial. A known fiducial is a

marking or location whose coordinates are known by accurately measuring the coordinates in relation to the origin. The coordinates of a fiducial can be measured using a laser plane, tape measure, and/or other suitable methods. The pan encoder reading in degrees (θ) is noted. The x,y coordinates of the fiducial (x_1, y_1) are noted. The x, y coordinates of the camera are noted (x_2, y_2). An angle α is determined as:

$$\alpha = \tan^{-1}((y_1 - y_2)/(x_1 - x_2)).$$

The pan registration variable is computed as:

$$\text{pan/reg} = 180^\circ - \theta - \alpha.$$

The tilt parameter is defined as ($\text{tilt} = \text{ptzfdit.tilt} - \text{level_tilt}$), where ptzfdit.tilt is measured with the tilt optical encoder during the event. The variable level_tilt represents the output of the tilt optical encoder at level tilt. Level tilt is the tilt of the camera when the optical axis is perpendicular to the force of gravity. Level tilt is found by setting a laser plane next to the camera at the level of the camera's lens. A stick or other object that can be used to view the marking from the laser plane should be placed across the stadium at a height to receive the beam. By pointing the optical center of the camera on the point illuminated on the stick by the laser plane across the stadium, the camera is brought to level tilt. The level_tilt parameter is the encoder reading, in degrees (or radians) at level tilt.

The twist parameter is determined by pointing the camera at the field (or other portion of an environment) and the output of the camera is sent to a computer. The image of the camera is superimposed over a transformed image of

a model of the environment. A slider on a graphical user interface (GUI) is used to alter the twist of the camera image so that it completely aligns with the image of the model. The degree of alignment correction is recorded as the twist parameter. Note that the transformation of the image of the model is performed with the best parameters known at the time.

5 The nodal_dist variable (used below) is the distance from the pan axis to the nodal point of the camera model. The distance is positive in the direction of the camera along the optical axis through the front piece of glass on the lens of the camera. The nodal point is the position of the camera's virtual point of view
10 measured as a distance forward of the pan axis when the camera is in the horizontal position. The variable, nodal_dist, changes for different zoom percentages and extender settings of the camera. The manufacturer of the lens can provide values that determine nodal_dist at different zoom percentages and extender settings. In one example, the manufacturer of the lens can provide a table of the distance of the
15 nodal point from the front piece of glass on the lens for each extender setting and a range of zoom percentages. For example, if the distance of the nodal point from the front piece of glass on the lens is dp yards, and the length of the lens is lens_len yards, then $\text{nodal_dist} = \text{lens_len} - \text{dp}$, where nodal_dist is measured in yards. If data from the manufacturer of the lens is not available, the information can be
20 measured on an optical bench and a lookup table built as a function of zoom position, focus, and 2X Extender setting. The information of the lookup table is measured by placing two targets in the view of the camera, off-center, one farther away than the other, so they appear in line through the viewfinder. Where a line extended through those targets intersects the optical axis of the camera is the
25 position of the nodal point or virtual point of view.

The coordinates (cx,cy,cz) are the world coordinates of the location of the

camera, which is defined as the intersection of the pan axis and the optical axis when the tilt is level and the pan measures zero on the pan encoder. The coordinates (lx,ly,lz) are the world coordinates of the nodal point of the camera model for a given tilt, pan, zoom, and extender setting of the camera. The
5 coordinates (lx,ly,lz) are defined by: (lx,ly,lz) = (cx,cy,cz) + (nx,ny,nz), where (nx,ny,nz,1) = (0,nodal_dist,0,1)[Rx,tilt][Ry,pan]. The matrix [Rx,tilt] is defined as:

$$[Rx,tilt]=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(tilt) & \sin(tilt) & 0 \\ 0 & -\sin(tilt) & \cos(tilt) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

10 and the matrix [Ry,pan] is defined as

$$[Ry,pan]=\begin{bmatrix} \cos(pan) & 0 & -\sin(pan) & 0 \\ 0 & 1 & 0 & 0 \\ \sin(pan) & 0 & \cos(pan) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

After using the transformation matrices, the system takes into account lens distortion. That is, each two-dimensional pixel position is evaluated in order to
15 determine if the two-dimensional position should change due to lens distortion. For a given two-dimensional pixel position, the magnitude of a radius from the optical center to the two-dimensional pixel position is determined. Lens distortion is

accounted for by moving the pixel's position along that radius by an amount ΔR :

$$\Delta R = K(R)^2$$

where

R = pixel distance from optical center to two-dimensional position

K = distortion factor.

5 At a fixed focus, the distortion factor is measured at a number of zoom values using a GUI slider to align the model to the video. These values are used to generate a distortion curve. During operation, the distortion factor at the current zoom is interpolated from the curve and applied to all transformed two-dimensional pixel positions points. The distortion data can also be obtained from the lens
10 manufacturer or can be measured by someone skilled in the art.

 The foregoing detailed description of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously many modifications and variations are possible in light of the above teaching. The described
15 embodiments were chosen in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. The invention is, thus, intended to be used with many different types of live events including various sporting events and non-
20 sporting events. It is intended that the scope of the invention be defined by the claims appended hereto.